Extra Dimensions and Black Hole Production[a]

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If nature realizes TeV scale gravity, we are entering a very exciting period in which we could be able to address, experimentally, some questions on quantum gravity, strings, branes and other exotic aspects of the fundamental theory of gravity. This article reviews recent development in models with Large Extra Dimensions and Black hole production at future colliders. Experimental results from current experiments as well as the expectation for the future colliders are summarized.

1 Introduction

The Standard Model (SM) has proved to be enormously successful in providing a description of particle physics up to energy scales of several hundred GeV as probed by current experiments [1]. In the SM, however, one assumes that effects of gravity can be neglected, because the scale where such effects become large is the Planck Scale. The question of why the $4-$dimensional Planck Scale, $G_{Pl}^{-1/2} \sim 10^{19}$ GeV, is much larger than the electroweak (EWK) scale, $G_{\mathcal{F}}^{-1/2} \sim 10^2$ GeV, is an outstanding problem in contemporary physics. The *hierarchy problem* is in the essence the difficulty to explain the large disparity between these two numbers [2].

Motivated in part by naturalness issues, numerous scenarios have emerged recently, that address the hierarchy problem within the context of the old idea that some part of the physical world (i.e. the SM-world) is confined to a brane in a higher dimensional space [3]. Although supergravity theories were formulated up to 11 dimensions and Superstring theories in 10 dimensions were known since the 70's, the idea to extend this extra spatial dimension paradigm (ESD) to other contexts, received a new impulse only recently [4]. As we don't experience in our everyday world, more then 3 spatial dimensions, we have to assume that any possible ESD is hidden.

There is a simple and elegant way to hide possible extra spatial dimensions: the *compactification*. The result is achieved by assuming, for example, that the extra dimensions form, at each point of the $4-$dimensional space, a torus of volume $(2\pi)^{\mathcal{D}} R_1 R_2 ... R_{\mathcal{D}}$. In this way it is possible to allow the gravity to live in the $\mathcal{D}$ large extra dimensions, the *bulk*, while the SM fields will lie on a 3-$\mathcal{D}$ surface, the *brane*.

In presence of a compactfied extra spatial dimension y, a field $\phi(x_\mu, y)$ of mass m_0 is periodic over y and can be Fourier developed as follow:

$$\phi(x_\mu, y) = \sum_{k=-\infty}^{+\infty} e^{\frac{iky}{R}} \phi^{(k)}(x_\mu) \tag{1}$$

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where R is the radius of the compact ESD. The $4\mathcal{D}$ terms $\phi^{(k)}(x_\mu)$ are the Kaluza-Klein states (KK), also called *modes* or *excitations*. The mass of each KK mode is then expressed by the formula:

$$m_k^2 = m_0^2 + k^2/R^2 \qquad (2)$$

If $M_\mathcal{F}$ is the actual fundamental scale of gravitational interactions and if V_{extra} is the volume of the extra dimensional $\mathcal{D}-$fold, then, by Gauss's law, at distances larger than the inverse mass of the lightest KK mode in the theory, the gravitational force will follow an inverse square law with an effective coupling of:

$$M_{Pl}^{-2} = M_\mathcal{F}^{-(\mathcal{D}+2)} V_{extra}^{-1} \qquad (3)$$

We see indeed that gravity becomes strong in the full $4 + \mathcal{D}-$dimensional space at a scale $M_\mathcal{F}$ of few TeV which is far below the conventional Planck Scale ($M_{Pl}^2 = M_\mathcal{F}^{\mathcal{D}+2} V_{extra}$).

At the present there are many models which assume the existence of extra spatial dimensions predicting the appearance of new physics signatures that can be probed at energy scale above $1\ TeV$. Most of the models fall into one of the three following classes:

1.1 The Large Extra Dimensions Scenario

The large extra dimension scenario (LED) started with the works of Arkani-Hamed, Dimopoulos and Dvali (ADD) [4,5]. In this model the SM particles live on a $3 + 1-$dimensional space ($3-$brane) while the gravity is free to propagate in higher-dimensional space, extra dimensions. This model predicts essentially the emission and exchange of large Kaluza-Klein towers of gravitons that are finely-spaced in mass. The ADD Model was first proposed to solve the hierarchy problem by requiring the compactified dimensions to be of very large size.

1.2 KK gauge bosons

A second possibility comes from all those models where the extra spatial dimensions are of TeV scale size. In these class of models there are KK excitations of the SM gauge fields with masses of the order a TeV which can show up in collider experiments as resonances.

1.3 Warped Extra Spatial dimension

Another approach for extra spatial dimensions has been proposed by L. Randall and R. Sundrum (RS models or WED) [6]. In this scenario two $4\mathcal{D}$ branes with tension V and $V^{'}$ are situated in the position, $y = 0$ and $y = \pi r_c$, of a $5\mathcal{D}$ bulk with cosmological constant λ, where the gravitation lives. One of the interesting consequence of this assumptions is the fact that the fundamental mass scale on the brane at $y = 0$ is then red-shifted by a factor $e^{-2k|y|}$ (*warp factor*) on the other brane at $y = \pi r_c$. In this way the EWK scale ($\mathcal{O}(1\ TeV)$) can be produced from

Observation & Object	$f_{\mathrm{KK}}^{\mathrm{max}}$		M^{min} [TeV]	
	$n = 2$	$n = 3$	$n = 2$	$n = 3$
Neutrino signal				
SN 1987A [7,8,9,10]	0.5	0.5	31	2.75
EGRET γ-ray limits				
Cosmic SNe [11]	0.5×10^{-2}	0.5×10^{-2}	84	7
Cas A	0.8×10^{-2}	0.3×10^{-2}	87	8
PSR J0953+0755	2.2×10^{-5}	0.9×10^{-5}	360	22
RX J185635–3754	0.5×10^{-5}	1.8×10^{-6}	540	31
Neutron star excess heat				
PSR J0953+0755	0.5×10^{-7}	0.5×10^{-7}	1680	60
GLAST γ-ray sensitivity				
RX J185635–3754	1×10^{-7}	0.5×10^{-7}	1300	60

Table 1: Constraints on the fundamental scale $M_{\mathcal{F}}$ coming from SN and neutron stars.

the Planck Scale. In the RS model the $4\mathcal{D}$ Planck mass is then expressed by the formula:

$$M_{Pl}^2 = \frac{M_5^3}{k}[1 - e^{-2kr_c\pi}] \qquad (4)$$

2 Experimental Astrophysical Constrains on LED

Various astrophysical and cosmological processes can be used to set limits on the model with extra dimensions. The phenomenology of the Supernova SN1987A places strong constrains on the energy loss mechanism, allowing to derive a bound on the fundamental Planck Scale. In fact if LED exist, then the usual $4D$ graviton is complemented by a tower of Kaluza-Klein states, corresponding to the new available phase space in the bulk. These KK gravitons would be emitted from the Supernova core after collapse, complete with neutrino cooling, and shorten the observable signal. This argument has led to the following bounds that require that the fundamental scale be as high as $M \geq 84\ TeV$ assuming $N = 2$ or $M \geq 7\ TeV$ for $N = 3$ [12]. The limits on the fundamental scale $M_{\mathcal{F}}$ coming from SN and neutron star data are summarized in Table 1.

Other effects are the possible distorsion of the cosmic diffuse gamma background because of the new accessible production mechanism: $G_{KK} \to \gamma\gamma$ decays. Using the COMPTEL data in the E_γ range $[800\ KeV - 30\ MeV]$, Hall and Smith set a lower limit on effective Planck scale $M_{\mathcal{F}}$ as function of the number of LED ($\mathcal{D}$): $M_{\mathcal{F}} > 100\ TeV$ ($\mathcal{D} = 2$) and $M_{\mathcal{F}} > 5\ TeV$ ($\mathcal{D} = 3$) [13]. Analogous analysis performed by Hannestad and Raffelt on EGRET data ($E_\gamma \sim [3 - 200]\ MeV$) set a limit on $M_{\mathcal{F}}$ as function of the number of LED: $M_{\mathcal{F}} > 84\ TeV$ ($\mathcal{D} = 2$) and $M_{\mathcal{F}} > 7\ TeV$ ($\mathcal{D} = 3$) [11].
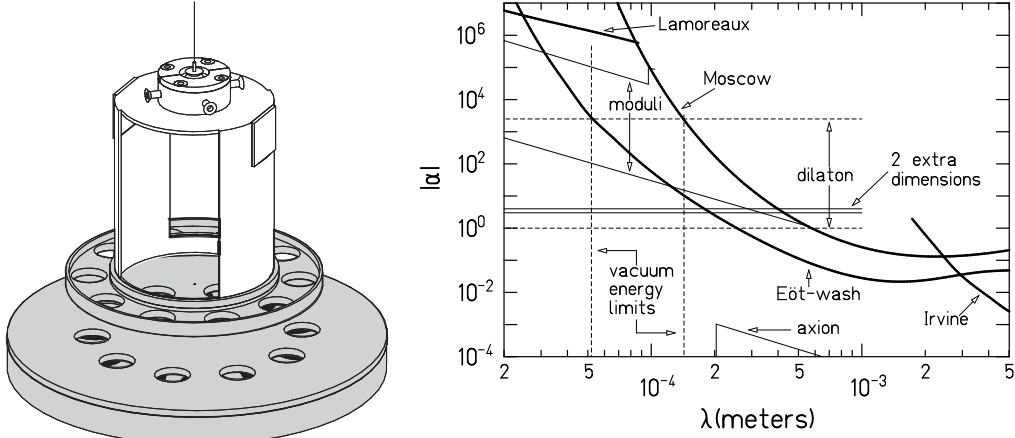
Figure 1: *a) Scale drawing of the torsion pendulum and rotating attractor; the active components are shaded and the distance between these two parts have been enhanced for clarity. b) 95% C.L. upper limits on the violation of the $1/R^2$ Newton Law as described in equation 5. The regions excluded by previous works lies above the lines labeled Irvine, Moscow and Lamoreaux, respectively.*

3 Direct Gravity Experiments

Until the middle of 1970 years a number of Cavendish-type experiments, searching also for the so called "fifth forth", have been performed in order to test possible deviation of Newton's gravitational interaction. This kind of experiments tested with good precision the Newton's law for a mass separation greater than 1 *cm*. As a matter of fact, in such experiments, the sensitivity vanishes quickly for distances below 1 *mm* because of the effects due to the Casimir and Van der Waals forces. Short-range regime of gravitation was not explored further because it was generally assumed that non-relativistic gravity obey an $1/R$ law for all $R >> R_{Pl} = \sqrt{G\hbar/c^3}$. The higher-dimensional theories described above suggest nowadays that new effect may show up at short distances. The string theory in particular predict scalar particles as *moduli* or *dilatons* that generate Yukawa interactions which could modify the Newton Gravitational Potential:

$$V(R) = -G\frac{m_1 m_2}{R}\left(1 + \alpha e^{-R/\lambda}\right) \tag{5}$$

In the simplest scenario, with a number of extra spatial dimensions equal to 2, we obtain the following values for λ and α: $\lambda = R^*$, $\alpha = 3$ for a compactification on an 2-sphere and $\lambda = R^*$, $\alpha = 4$ for a compactification on an 2-torus, where R^* is the extra dimension radii:

$$R^* = \frac{\hbar c}{M^* c^2}\left(\frac{M_{Pl}}{M^*}\right) \tag{6}$$

and M^* is the unification scale (usually taken as M_{SM}). Recently sub-millimeter test of the gravitational inverse-square law have been performed by C.D. Hoyle *et al.*[14] using a 10-fold symmetric torsion pendulum and a rotating 10-fold symmetric attractor. A schematic description of the experimental setup is given in Fig. 1.a. The results obtained, if interpreted in the simplest unification scenario with 2 equal large extra dimensions, imply a unification scale of $M^* \geq 3.5 \, TeV$ (see Fig. 1.b).
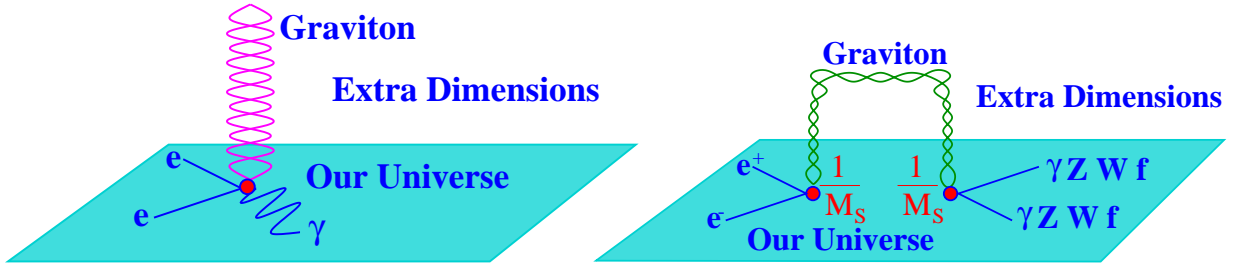
Figure 2: *Direct graviton emission diagram contributing to the process $e^+e^- \to \gamma G$ (left); Virtual graviton exchange diagrams (right).*

4   LED at present collider Experiments

Most of the searches performed until now for large extra dimensions have been done assuming the ADD phenomenology. We summarize here signatures and results of such searches.

As Kaluza-Klein gravitons couple to the momentum tensor, they therefore contribute to most of the SM processes. Depending on whether the G_{KK} leaves our world or remains virtual, the collider signatures change. For graviton that propagate in the bulk, in particular, from the point of view of our 3+1 space-time, energy and momentum are not conserved in the G_{KK} emission. Gravitons, on the other hand, interacting weakly with detectors, escape detection causing a typical missing transverse energy ($\not{E}_T$) signal. We will summarize in the next two paragraphs the different classes of signatures that correspond experimentally to the real and to virtual graviton emissions.

4.1   Real Graviton Emission

Direct emission of gravitons leads to the presence of missing energy in the final state. At e^+e^- colliders the best signal is the associated production of gravitons with a Z boson, a photon, or a fermion pair. In the hadron colliders the prominent and most studied signature is the production of one jet (monojet) associated with large transverse energy in the final state.

The effects of direct graviton production, including single photon or Z's production, have been studied at LEPII[15,16]. The following final states have been considered in the analysis: $\gamma+\not{E}_T$, $Z(\to jj)+\not{E}_T$ (see Fig. 2). With no excess apparent beyond the SM expectations, a lower limit on the graviton contribution have been calculated at 95% Confidence Level. The limits, expressed in terms of effective Planck Scale, are summerized in Table 2.

The CDF and DØ Collaborations at the Fermilab Tevatron Collider also looked for direct graviton emission. From an experimental point of view the mono-jet plus missing$-\not{E}_T$ signature is quite complex to study because of the large instrumental background from jet mismeasurement and the presence of cosmic rays background. Results on this channel will be available soon.

4.2   Virtual Graviton emission

The virtual exchange of graviton towers either leads to modifications in SM cross sections and asymmetries or to new processes not allowed in the SM at the tree level. Collider signatures with virtual exchanges of $KK-$gravitons are several and include diphoton, diboson and fermion-pair production. In the case of virtual G_{KK}

	N=2		N=4		N=6	
	$M_D(TeV)$	$R(cm)$	$M_D(TeV)$	$R(cm)$	$M_D(TeV)$	$R(cm)$
ALEPH	1.28	$2.9 \cdot 10^{-2}$	0.78	$1.4 \cdot 10^{-9}$	0.57	$5.6 \cdot 10^{-12}$
DELPHI	1.38	$2.5 \cdot 10^{-2}$	0.84	$1.3 \cdot 10^{-9}$	0.58	$5.4 \cdot 10^{-12}$
L3	1.45	$2.3 \cdot 10^{-2}$	0.87	$1.2 \cdot 10^{-9}$	0.61	$5.2 \cdot 10^{-12}$

Table 2: *95% C.L. lower limits on the gravitational scale M_D and on the size of extra dimensions R, derived from the direct graviton searches in the $e^+e^- \to \gamma G$ channel*

emission, gravitons lead to apparent violation of 4-momentum as well as of the angular momentum.

There are several processes that can be studied at lepton colliders [17]: $e^+e^- \to \gamma\gamma$, e^+e^-, W^+W^-, Z^0Z^0 (see Fig. 2). Among many fermion and boson-pair final states studied at LEP, the most sensitive channels involve Bhabha scattering ($e^+e^- \to e^+e^-$) and the photon-pair production ($e^+e^- \to \gamma\gamma$). The lower limits at 95% C.L. on $M_\mathcal{F}$ obtained using the e^+e^- and $\gamma\gamma$ channel are given in Table 3 and in Table 4. The combined limit, as obtained by assuming log likelihood curves from different channels, is $M_\mathcal{F} > 1.03\ TeV$ for $\lambda = +1$ and $M_\mathcal{F} > 1.17\ TeV$ for $\lambda = -1$.

λ	L3	OPAL
$\lambda = +1$	1.06	1.00
$\lambda = -1$	0.98	1.15

Table 3: *95% C.L. lower limits on $M_\mathcal{F}$ obtained by L3 and OPAL using the Bhabha scattering process: $e^+e^- \to e^+e^-$; results are shown in Hewett notation.*

The impact of virtual gravitons in hadron collider experiments can be observed in processes such as: $q\bar{q} \to G \to \gamma\gamma$ or $gg \to G \to e^+e^-$ where the ADD model introduces production mechanism that can increase the cross-section of diphoton and dielectron production at high invariant mass over the SM. The diphoton and dielectron cross-section considering the LED contributions take the form [5]:

$$\frac{d^2\sigma_{Tot}}{dcos\theta^*\ dM} = \frac{d^2\sigma_{SM}}{dcos\theta^*\ dM} + \frac{a(n)}{M_\mathcal{F}^4}\ F_1(cos\theta^*, M) + \frac{b(n)}{M_\mathcal{F}^8}\ F_2(cos\theta^*, M) \qquad (7)$$

where $cos\theta^*$ is the scattering angle of the photon or electron in the center of mass frame of the incoming parton. The first term in the expression 7 is the pure SM contribution to the cross section; the second and the third part are the interference term and the direct G_{KK} contribution. The characteristic signatures for contributions from virtual G_{KK} correspond to the formation of massive systems abnormally beyond the SM expectations. Figure 3 shows a comparison of the two-dimensional distributions in di-EM mass and $|cos\theta^*|$ for data, SM background processes and for background plus LED contribution as obtained by DØ Collaboration. With no excess apparent beyond expectations of the SM, D0 proceeds to calculate a lower limit on the graviton contribution to the di-EM cross section. Hence there are three main formulation on the effective lagrangian the Giudice, Rattazzi and Wells (GRW) [18], the Han, Lykken and Zhang (HLZ) [19] notation and the Hewett [20] one the limits in

λ	ALEPH	DELPHI	L3	OPAL
$\lambda = +1$	0.81	0.82	0.83	0.83
$\lambda = -1$	0.82	0.91	0.99	0.89

Table 4: *95% C.L. lower limits on $M_\mathcal{F}$ obtained using $\gamma\gamma$ channel; the results are given in the Hewett formulation.*

the Table 5 are translated in all this notations as well as function of the number of extra dimensions for the HLZ approach [21].

The CDF Collaboration performed a similar search using the dielectron and diphoton channels. The combined results expressed in the Hewett convention for $\lambda = +1$ is $M_\mathcal{F} > 0.814\ TeV$ and for $\lambda = -1$ are $M_\mathcal{F} > 0.9\ TeV$ [22].

More studies are forthcoming from CDF and DØon real graviton emission (mono-jet events), as well as on virtual graviton exchange, which by the end of Run-II, should be sensitive to scales of $2 - 3\ TeV$. Beyond that lies LHC which sensitivity should cover a mass region up to $M_\mathcal{F} \sim 10\ TeV$ [23]. The sensitivity of Tevatron and LHC experiments on $M_\mathcal{F}$ for $\mathcal{D} = 4$ is summarized in Table 6.

5 LED Searches at Future Colliders

Different signatures for several extra dimensional models have been studied recently in order to understand which results will be possible to obtain at future lepton colliders such as CLIC or hadron colliders as the Very Large Hadron Collider (VLHC) (see Table 6).

CLIC is an e^+e^- collider with an expected center of mass of energy ranging between 3 and 5 TeV. With and integrated luminosity of 1 ab^{-1} for many of the extra dimensional models the experimental reach is found to be in the interval of $\sim 15-80$ TeV [24].

The VLHC is a hadron collider thought to be build in 2 steps: a stage I in which the avaible center of mass energy will be $40\ TeV$ and a stage II when, by using new magnets, the center of mass energy could reach a value of 175 or 200 TeV. In particular, as have been shown by T. Rizzo [25] a 200 TeV VLHC with 1 ab^{-1} of an integrated luminosity will be able to observe the first $RS\ KK$ excitation for masses as large as $15 - 30\ TeV$ and values of $M_\mathcal{F} \sim 50 - 60\ TeV$, in the ADD model, will be directly probed in the Drell-Yan processes.

6 Black Hole Production at Hadron Colliders

Since long ago, black holes (BH) have been objects of interest in theoretical physics and astrophysics, and more recently also in experimental high energy physics. As a matter of fact, BH can be produced in a particle collisions if the center of mass

Comparison of the data and the SM predictions
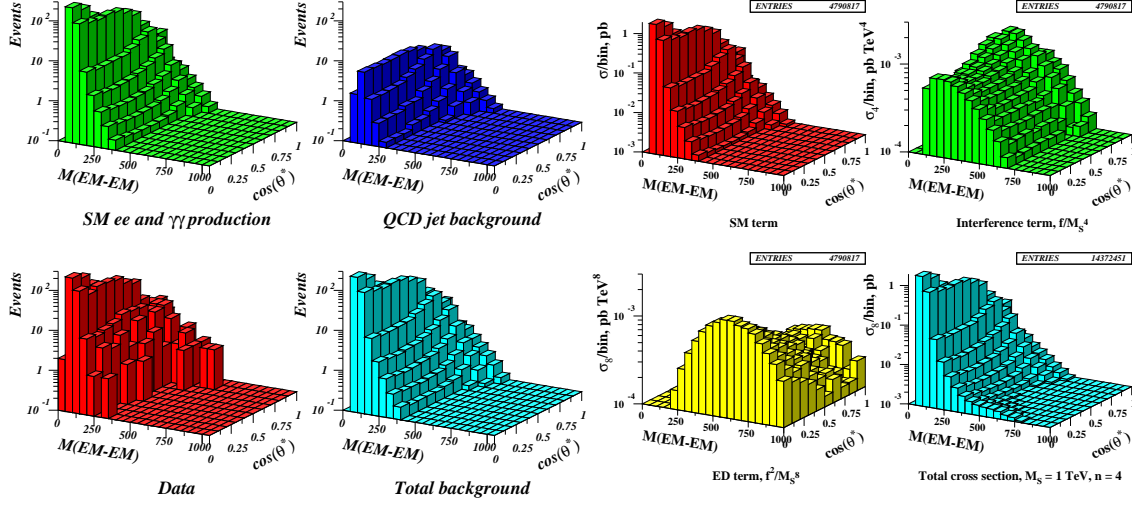
MC Simulation of the ED signatures

Figure 3: a) Comparison in the M_{EM-EM} vs $|cos(\theta^*)|$ plane of Data with Monte Carlo for SM processes ($EM = \gamma$ or e); b) same as in a) including also the LED contributes.

energy is above the Planck Scale ($\sqrt{s} > M_{Pl}$). In LED models the Planck Scale can be effectively $\mathcal{O}(1\,TeV)$, opening up the interesting possibility of producing and studying BH using collider experiments [26]. The observability of such BH at future colliders will depend on the value of the fundamental Planck Scale. At Hadron colliders, where it is possible to reach the highest center of mass energies, compared to other machines, the BH production cross section can be written as follow:

$$\sigma_{pp \to BH}(M_{min}, s) = \sum_{ij} \int_{\tau_m}^1 d\tau \int_\tau^1 \frac{dx}{x} F_i(x) F_j(\tau/x) \sigma_{ij \to BH}(\tau s) \qquad (8)$$

where i and j are the two colliding partons, x and τ/x are the momentum fractions of i and j and F are the parton distribution functions. If we assume the Thorne's hoop conjecture, that states that horizons form when and only when a mass M is compacted into a region whose circumference in every directions is less than $2\pi R_{BH}(M)$, we obtain the important result that the black hole production cross section is :

$$\sigma_{ij \to BH}(s) \sim \pi R_{BH}^2(\sqrt{s}) \qquad (9)$$

The precise mass of the BH formed in a collision depends on the amount of energy and matter which becomes trapped behind the event horizon. If the scale of gravity is the TeV scale, BH production could be a dominant process at hadron colliders

GRW [18]	HLZ [19]						Hewett [20]	
	$n{=}2$	$n{=}3$	$n{=}4$	$n{=}5$	$n{=}6$	$n{=}7$	$\lambda = +1$	$\lambda = -1$
1.2	1.4	1.4	1.2	1.1	1.0	1.0	1.1	1.0

Table 5: Lower limits at 95% CL on the effective Planck Scale, M_S, in TeV.

beyond LHC. For example for $M_{Pl} = 1\,TeV$ and $\mathcal{D} = 10$, at the Very Large Hadron Collider (VLHC) considering $\sqrt{s} = 100\,TeV$ (something in the middle between the stage I and the stage II) assuming an integrated luminosity per year of $100\,fb^{-1}yr^{-1}$, BH of mass around $10\,TeV$ should be produced with a rate of $1\,Kz$.

6.1 Black Hole decays and signatures

Once produced black holes decay. The decay process is rather complex and occurs in several stages [27]:

1. *Balding Phase*: in which there is emission of gauge and gravitational radiation that will settle down the BH to a symmetrical rotating object with a growing horizon;

2. *Spin-down Phase*: in which the BH Hawking radiates, emitting quanta having angular moment $\ell \sim 1$;

3. *Schwarzschild-Hawking Evaporation Phase*: The Spin-down phase leaves a Schwarzschild BH that continues to radiate Hawking Radiation; instant quanta are emitted with a thermal spectrum around Hawking temperature (T_H);

4. *Planck Phase* Once the BH reach the Planck Mass $M \sim M_p$ the BH completely decays emitting few quanta with energies $\mathcal{O}(M_p)$;

Because of the large cross section, multiplicity and visible energy, BH, at hadron colliders, give rise to very spectacular events. The BH production and decay is characterized by the following specific signatures [28,29]:

- suppression of hard perturbative scattering processes at energy in which the BH production start to dominate;

- very large production cross sections that grows with the energy;

- high multiplicity events (for $M_{BH} \sim 10\,TeV$, $\mathcal{D} = 10$ the expected multiplicity is ~ 50) with visible transverse energy of the order of $\sim 1/3$ of the total energy;

- high sphericity events because of the small BH boost $(\langle \gamma \beta \rangle < 1)$;

- a ratio of $\sim 1/5$ between leptonic and hadronic activity because of the Schwarzschild-Hawking Evaporation Phase.

(a) Hadron Colliders				(b) e^+e^- Colliders					
Run I	Run IIa	Run IIb	LHC	$\sqrt{s} = 0.5$ TeV		1 TeV		1.5 TeV	
$\mathcal{L} = 0.13$ fb^{-1}	2	20	100	$\mathcal{L} = 10$ fb^{-1}	50	50	100	100	200
1.3	1.9	2.6	9.9	3.9	4.8	7.9	8.9	12.0	13.0

Table 6: 95% C.L. sensitivity limits on M_S ($n = 4$) at (a) hadronic colliders (Tevatron and LHC) and (b) e^+e^- colliders of 0.5 – 1.5 TeV.

7 Black Hole production and Cosmic Rays

There are other possibilities to study experimentally the Black Hole production associated with the existence of extra spatial dimensions. Black Holes, in fact, may be produced by inelastic scattering of ultra-high energy cosmic neutrinos with the matter. As Black Hole decays give rise to deeply penetrating showers, with an electromagnetic component which differs substantially from the conventional neutrino interactions [30], it is possible to reach good signal on background discrimination. At the present BH production can be studied using cosmic rays in the interaction with air nuclei and detected by air shower arrays like in the case of the Auger Experiment [31,32], or in the interaction with ice or water nuclei like in the case of neutrino telescopes such as AMANDA, IceCube [33,34] and RICE [35]. These cosmic ray opportunities can be realized before the start of the physics run of the Large Hadron Collider.

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